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Weed control and water-seeded rice response to pyraclonil applied at different timings and in herbicide combinations

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Abstract

Pyraclonil is a new herbicide to control weeds in California water-seeded rice (*Oryza sativa* L.). The objectives of this research were to evaluate weed control and rice response from pyraclonil applied alone at different timings and when applied in combinations with other herbicides. In one field study, pyaclonil was applied at 0.3 lbs a.i. ac^{-1} on pre-seed bare ground, 1-inch flood, 4-inch flood and 3 days after flooding in water-seeded rice. In another study, pyraclonil was applied at 0.3 lbs a.i. ac^{-1} at day of rice seeding and followed by various registered herbicides. Pyraclonil applications resulted in similar weed control across timings. Pyraclonil provided greater than 92% control of smallflower umbrella sedge (*Cyperus difformis* L.) and broadleaf weeds but less than 60% control of ricefield bulrush [S*choenoplectus mucronatus* (L.) Palla] at 42 days after treatment. Watergrass (*Echinochloa* spp.) control was achieved with pyraclonil if applied before emergence. Early-season rice injury from pyraclonil was observed; however, rice appeared uninjured later in the season. The addition of other herbicides after a pyraclonil application increased weed control levels across weed species and resulted in grain yields from 6,925 to 8,623 and 9,182 to 10,865 lbs ac^{-1} in 2019 and 2021, respectively. Pyraclonil provides early-season weed control and, when incorporated with other herbicides, will be a useful herbicide in water-seeded rice.

Plain Language Summary

Pyraclonil is a new Group 14 herbicide available for early-season weed control in California water-seeded rice. We aimed to understand weed control and water-seeded rice response from pyraclonil applied at different timings and in combination with currently registered herbicides. The application of pyraclonil at 0.3 lbs a.i. ac^{-1} at pre-seed bare ground, 1-inch flood, 4-inch flood, and 3 days after flooding resulted in similar weed control. Control of smallflower umbrella sedge and broadleaf weeds was 92% or greater with pyraclonil. Watergrasses were controlled when applied before

Abbreviations: DAF, days after flooding; DAT, days after treatment; DOS, day of seeding; PPO, protoporphyrinogen oxidase.

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their emergence, and starting out with a field with no watergrass emergence is critical. Other herbicide combinations are necessary for season-long weed control of ricefield bulrush and weedy grasses. Rice injury from pyraclonil was observed early in the season, but the rice appeared uninjured later in the season and rice yields resulted similar across treatments in both studies.

1 | INTRODUCTION

California is the second largest rice (*Oryza sativa* L.) producing state in the United States with nearly 500,000 acres in production planted in the Sacramento and Northern San Joaquin Valley (USDA, 2023). Greater than 90% of rice produced in California is medium-grain rice (UCANR, 2023). Water-seeded rice is common practice for rice production in California; which is the practice of air-seeding pregerminated rice seed onto fields with a 4-inch standing flood, then, continuously flooded throughout the growing season (Hill et al., 2006). The water-seeded production system was implemented to control weedy grasses and non-aquatic weeds (Hill et al., 2006).

Weed interference is the major constraint to achieving adequate grain yields in rice production systems (Brim-DeForest et al., 2017; Hill et al., 2006). In the California water-seeded rice agroecosystem, the major weeds that interfere with rice include watergrasses (*Echinochloa* spp.), bearded sprangletop [*Leptochloa fusca* (L.) Kunth ssp. *fascicularis* (Lam) N. Snow]; sedges such as smallflower umbrella sedge (*Cyperus difformis* L.) and ricefield bulrush [*Schoenoplectus mucronatus* (L.) Palla]; and broadleaves including ducksalad (*Heteranthera limosa* L.), water hyssop (*Bacopa* spp.), and redstem (*Ammannia* spp.) (Brim-DeForest et al., 2017). Rice grain yield reductions of up to 79%, 44%, and 30% can be caused by weedy grass, sedges, and broadleaves, respectively (Smith, 1968; Swain et al., 1975, 1995).

Herbicides continue to be an important tool for weed management in rice (UCANR, 2023). Herbicide resistance is a continuing challenge in California rice that results in reduced control with currently available herbicides (Becerra-Alvarez et al., 2023; Hill et al., 2006). The lack of herbicides available have encouraged efforts to evaluate new herbicides that would help growers manage herbicide-resistant populations and practice appropriate mode of action rotations (Becerra-Alvarez et al., 2023).

Pyraclonil is a protoporphyrinogen oxidase (PPO)-inhibitor (Group 14) (Wang et al., 2021). It is a broad-spectrum pre-emergent herbicide largely used in Asian rice production systems with activity on broadleaves and grasses (Wang et al., 2021; Zhang, 2014). In Asia, pyraclonil is used to control herbicide-resistant weed biotypes and is useful when incorporated in season-long weed management programs (Hamamura, 2018; Liu et al., 2021). The US Environmental Protection Agency has recently approved the registration of pyraclonil (Zembu™, Nichino America Inc.) in the US for early-season weed control in water-seeded rice (US EPA, 2023).

There is no previously published research examining pyraclonil control on California rice weeds and water-seeded rice response. Therefore, the objectives of these studies were to examine pyraclonil weed control and rice response at different application timings and in herbicide combinations with currently registered herbicides in the water-seeded rice system.

2 | FIELD METHODS

The studies were conducted at the Rice Experiment Station in Biggs, CA (39°27′8.0964″ N, 121°43′14.6532″ W). The pyraclonil application timing study was conducted in 2019, 2020, and 2023. The study on pyraclonil application in combination with other herbicides was conducted in 2019 and 2021. Soils at the site are characterized as an Esquon-Neerdobe (fine, smectitic, thermic Xeric Epiaquerts and Duraquerts), silty clay, made up of 27% sand, 39% silt, and 34% clay, with a pH of 5.1, and 2.8% organic matter. Field preparation as suggested by the University of California recommendations was followed (UCANR, 2023). A granule fertilizer starter mixture (34% N, 17% P, 0% K) was applied by aircraft at 300 lbs ac^{-1}. Individual 10-ft wide by 20-ft long plots surrounded by 7-ft wide shared levees were made after fertilizing and prior to flooding to prevent contamination from adjacent treatments in a replication in both studies. Weather data of the field site is provided in the supplementary material (Figure S1; Figure S2; Figure S3).

The rice weeds present in the field site were barnyardgrass [*Echinochloa crus-galli* (L.) Beauv], early watergrass (*E. oryzoides*), late watergrass [*E. phyllopogon* (Stapff) Koss], bearded sprangletop, smallflower umbrella sedge, ricefield bulrush, ducksalad, water hyssop, and redstem. Because of the difficulties to identify *Echinochloa* spp. at early growth stages, all *Echinochloa* spp. were grouped together when evaluating weed control.

TABLE A Useful conversions.

To convert Column 1 to Column 2, multiply by	Column 1 Suggested Unit	Column 2 SI Unit
Length		
0.304	foot, ft	meter, m
2.54	inch	centimeter, cm (10^{-2} m)
Area		
0.405	acre	hectare, ha
Mass		
454	pound, lb	gram, g (10^{-3} kg)
Yield and Rate		
1.12	pound per acre, lb/acre	kilogram per hectare, kg/ha
Temperature		
5/9 (˚F – 32)	Fahrenheit, ˚F	Celsius, ˚C

2.1 | Pyraclonil timing

Seeds of the rice cultivar M-206 in 2019 and 2020, and 'M-209' in 2023 were pregerminated in steel bins filled with water. For disease control, a 5% sodium hypochlorite solution was added in the water for the first hour, then drained and refilled with only water for the remaining 24 hours, in accordance with University of California recommendations (UCANR, 2023). The seed was then drained until dry up to 12 hours, and seeded at 120, 120, and 150 lbs ac^{-1} seeding rates in 2019, 2020, and 2023, respectively.

Pyraclonil formulated as a dry granule at 1.8% active ingredient per weight was evenly spread by hand on each plot at 0.3 lbs a.i. ac^{-1} (14.9 lbs ac^{-1} of product). The seeding times and application timings for each treatment are stated in Table 1. The study was established in a randomized complete block design with four replications each year. After the treatment applications (Table 1), the 4-inch flood was maintained until harvest.

Visual weed control for individual weed species was collected at 14, 28, and 42 days after treatment (DAT) by using a scale of 0 to 100, where 0 = no control and 100 = plant death. Visual percent rice injury assessments were carried out at 7, 14, 28, and 42 DAT by observing present symptomology compared to the nontreated, which included stunting and stand reduction on a scale of 0 to 100, where 0 = no injury and 100 = plant death. Plant height was recorded at ripening stage by measuring from the soil surface to the highest leaf at two locations in each plot. Rice grain yield was collected from each plot with a small-plot combine all years and adjusted to 14% moisture.

2.2 | Pyraclonil herbicide combinations

M-206 rice cultivar was pregerminated in a similar manner as mentioned above, then, air-seeded at 120 and 150 lbs ac^{-1} in 2019 and 2021, respectively. Seeding dates were June 13, 2019, and June 1, 2021. Pyraclonil (1.8% active ingredient) was applied by hand at 0.3 lbs a.i. ac^{-1} onto plots with a 4-inch flood at day of rice seeding (DOS). The herbicide combinations were applied at their respective timings and labelled rates as presented in Table 2. The study was established in a randomized complete block design with four replications each year. The 4-inch flood was maintained and only lowered for application of foliar herbicide treatments and reflooded 48 hours after application.

Visual weed control for individual species was collected at 14 and 42 DAT on a 0 to 100 scale as described earlier. Visual rice injury assessments were conducted at 14 and 42 DAT on a 0 to 100 scale. Rice grain was harvested from each plot as described earlier and adjusted to 14% moisture.

The data was analyzed with mixed model regression analysis using R v.4.2.1 (Kuznetsova et al., 2017; R Core Team, 2023). The weed control and rice injury ratings were analyzed with assessment dates treated as a repeated measure in the pyraclonil timing study. Assessment dates was a fixed factor in the pyraclonil herbicide combinations study. Mean separation with Tukey's honestly significant difference at $\alpha = 0.05$ was implemented where appropriate. The 2019 and 2020 pyraclonil timing rice response data were pooled, while the 2023 rice response data is presented separately averaged over four replications with standard deviation as a variance measure.

3 | WEED CONTROL RESPONSE TO PYRACLONIL TIMING

Pyraclonil treatments resulted in similar weed control across timings (Table 3). Control of smallflower umbrella sedge was 96% and ricefield bulrush control was 60% by 42 DAT (Table 3). These differences are not surprising since the observed differential control level among the two sedges is also observed with carfentrazone (Shark H20, FMC), another PPO-inhibitor available for post-emergence use in California rice, which controls smallflower umbrella sedge but not ricefield bulrush (UCANR, 2023). The differential response may be because of different herbicide metabolism pathways or anatomical differences between species that lead to the herbicide not reaching the site of action (Menzani, 2017).

Broadleaf control was 94% or greater across all timings for ducksalad, water hyssop and redstem (Table 3). Pyraclonil controls broadleaves like *Sagittaria trifolia*, and *Monochoria vaginalis* in Asian rice fields (Wang et al., 2021). Broadleaves

TABLE 1 Pyraclonil application dates in the pyraclonil timing study in water-seeded rice at Biggs, California in 2019, 2020 and 2023.[a]

Treatment	Rate (lbs a.i. ac^{-1})	Timing	2019		2020		2023	
Pyraclonil	0.3	Pre-seed bare ground	June 13	0 DAS	May 20	3 DBS	May 28	3 DBS
Pyraclonil	0.3	1-inch flood	June 14	1 DBS	May 23	0 DAS	May 31	0 DAS
Pyraclonil	0.3	4-inch flood	June 15	2 DAS	May 26	3 DAS	June 2	2 DAS
Pyraclonil	0.3	3 DAF	June 19	4 DAS	May 26	3 DAS	June 3	3 DAS

Abbreviations: DAS, days after rice seeding; DAF, days after initial flood; DBS, days before rice seeding.
[a]The nontreated control plots was seeded at the same date as the 0 DAS.

TABLE 2 Herbicides, rates, and application timings of the pyraclonil applied alone and in combination with other herbicides applied on rice at Biggs, CA in 2019 and 2021.

Treatment	Herbicide	Trade name	Manufacturer	Mode of action group	Rate (lbs a.i. ac^{-1})	Application timing
T1	Pyraclonil	Zembu	Nichino America, Inc.	14	0.3	DOS
T2	Pyraclonil	Zembu	Nichino America, Inc.	14	0.3	DOS
	Propanil	SuperWHAM! CA	UPL NA	5	5.9	5-rice leaf stage
T3	Pyraclonil	Zembu	Nichino America, Inc.	14	0.3	DOS
	Benzobicyclon + halosulfuron	Butte	Gowan Company LLC	27 + 2	0.2	1.5-rice leaf stage
	Propanil	SuperWHAM! CA	UPL NA	5	5.9	5-rice leaf stage
T4	Pyraclonil	Zembu	Nichino America, Inc.	14	0.3	DOS
	Clomazone	Cerano 5 MEG	Wilbur-Ellis Company LLC	13	0.6	DOS
	Propanil	SuperWHAM! CA	UPL NA	14	5.9	5-rice leaf stage
T5	Pyraclonil	Zembu	Nichino America, Inc.	14	0.3	DOS
	Thiobencarb	Bolero UltraMax	Valent USA LLC	15	0.2	1.5-rice leaf stage
	Propanil	SuperWHAM! CA	UPL NA	5	5.9	5-rice leaf stage
T6	Pyraclonil	Zembu	Nichino America, Inc.	14	0.3	DOS
	Propanil	SuperWHAM! CA		5	5.9	5-rice leaf stage
	Bispyribac-sodium	Regiment CA	Valent USA LLC	2	0.02	Early rice tillering
T7	Pyraclonil	Zembu	Nichino America, Inc.	14	0.3	DOS
	Penoxsulam	Granite GR	Corteva AgriScience	2	0.2	3-rice leaf stage
	Propanil	SuperWHAM! CA	UPL NA	5	5.9	5-rice leaf stage
T8	Pyraclonil	Zembu	Nichino America, Inc.	14	0.3	DOS
	Propanil	SuperWHAM! CA	UPL NA	5	5.9	5-rice leaf stage
	Florpyrauxifen-benzyl	Loyant CA	Corteva AgriScience	4	0.03	Early rice tillering

Note. For the combination treatments including propanil, the spray mixture included 2.5% v/v crop oil concentrate (COC, Prime Oil, WinField Solutions LLC). For the combination treatment including bispyribac-sodium, the spray mixture included a multifunction adjuvant at 0.37 mL ha^{-1} (DyneAmic, Helena Agri-Enterprises LLC).
Abbreviation: DOS, day of seeding

are not difficult weeds to control in California rice because of the availability of several effective herbicides on broadleaf weeds (UCANR, 2023); however, there are herbicide-resistant populations to the available herbicides (Becerra-Alvarez et al., 2023; Hill et al., 2006). Therefore, pyraclonil can be a new herbicide to rotate modes of action and prolong effectiveness of available herbicides on broadleaf weeds.

There was treatment by years interaction for *Echinochloa* control (Table 4). Initiating with a clean weed-free field at time of flooding was critical to achieve good control. In general, *Echinochloa* control was greater than 95% in 2019 and 2023 at 42 DAT; however, in 2020, control levels were below 70% (Table 4). In 2020, the reduction in grass control occurred because of late rains in spring which totaled 0.7 inches of rain within four days before the first application (Figure S3) which led to a late rice planting date with moisture present in the soil by time of flooding. The soil moisture in 2020 allowed the grasses to be emerged by the time of the rice seeding

TABLE 3 Average sedge and broadleaf control as affected by pyraclonil applied at different timings in water-seeded rice pooled across 2019, 2020 and 2023.

Treatment	Rate (lbs a.i. ac^{-1})	Timing	DAT	Ricefield bulrush control	Smallflower umbrella sedge control	Ducksalad control	Water hyssop control	Redstem control
				% of nontreated				
Pyraclonil	0.3	Pre-seed bare ground	14	66ab	62d	94b	97ab	100
Pyraclonil	0.3	1-inch flood	14	72a	64bcd	95ab	97ab	100
Pyraclonil	0.3	4-inch flood	14	67ab	63cd	96ab	97ab	100
Pyraclonil	0.3	3 DAF	14	65ab	71abcd	95ab	97b	100
Pyraclonil	0.3	Pre-seed bare ground	28	62ab	92abc	98ab	98a	100
Pyraclonil	0.3	1-inch flood	28	70ab	95a	98ab	98a	100
Pyraclonil	0.3	4-inch flood	28	67ab	95	98ab	98a	100
Pyraclonil	0.3	3 DAF	28	60ab	91abcd	98ab	98a	100
Pyraclonil	0.3	Pre-seed bare ground	42	51b	92ab	100a	98ab	100
Pyraclonil	0.3	1-inch flood	42	55ab	96a	100a	98ab	100
Pyraclonil	0.3	4-inch flood	42	60ab	95a	100a	98ab	100
Pyraclonil	0.3	3 DAF	42	59ab	92abcd	100a	98ab	100
								NS

Note. Means with the same letter within each column do not differ by Tukey's honestly significant difference $\alpha = 0.05$. Assessment dates (DAT) were analyzed as a repeated measure.
Abbreviations: DAF, days after initial flood; DAT, days after treatment; NS, not significant.

TABLE 4 Echinochloa spp. control from pyraclonil at different application timings in water-seeded rice in 2019, 2020 and 2023.

Treatment	Rate (lbs a.i. ac^{-1})	Timing	DAT	2019	2020	2023
				Echinochloa control		
				% of nontreated		
Pyraclonil	0.3	Pre-seed bare ground	14	73c	42c	86c
Pyraclonil	0.3	1-inch flood	14	70c	39c	84c
Pyraclonil	0.3	4-inch flood	14	68c	38c	82c
Pyraclonil	0.3	3 DAF	14	67c	37c	81c
Pyraclonil	0.3	Pre-seed bare ground	28	92abc	61abc	100abc
Pyraclonil	0.3	1-inch flood	28	92abc	61abc	100abc
Pyraclonil	0.3	4-inch flood	28	91abc	60abc	100abc
Pyraclonil	0.3	3 DAF	28	92ab	65ab	100ab
Pyraclonil	0.3	Pre-seed bare ground	42	100a	70a	100a
Pyraclonil	0.3	1-inch flood	42	97ab	66ab	100ab
Pyraclonil	0.3	4-inch flood	42	95ab	65ab	100ab
Pyraclonil	0.3	3 DAF	42	98a	67a	100a

Note. Means with the same letter within each column do not differ by Tukey's honestly significant difference $\alpha = 0.05$. Assessment dates (DAT) were analyzed as a repeated measure. There was interaction by years, $P < 0.001$.
Abbreviations: DAF, days after initial flood; DAT, days after treatment.

and pyraclonil applications. In 2019, there was also precipitation before the seeding dates (Figure S3); however, glyphosate was applied to control the emerged grasses before preparation of the plot levees. These results demonstrate that when pyraclonil timing is before *Echinochloa* emergence, control can be achieved. The treatment timings tested in this study were not enough to cause significant differences in *Echinochloa* control and application within three days before or after the initial flood can provide 70% to 100% control when applied before *Echinochloa* emergence.

TABLE 5 Visual rice response as affected by pyraclonil application timings in water-seeded rice pooled across 2019, 2020 and 2023.

Treatment	Rate (lbs a.i. ac^{-1})	Timing	DAT	Visual injury[a]
				% of nontreated
Pyraclonil	0.3	Pre-seed bare ground	7	49abcd
Pyraclonil	0.3	1-inch flood	7	52ab
Pyraclonil	0.3	4-inch flood	7	58ab
Pyraclonil	0.3	3 DAF	7	79a
Pyraclonil	0.3	Pre-seed bare ground	14	31bcde
Pyraclonil	0.3	1-inch flood	14	40bcde
Pyraclonil	0.3	4-inch flood	14	31bcde
Pyraclonil	0.3	3 DAF	14	43abcde
Pyraclonil	0.3	Pre-seed bare ground	28	29bcde
Pyraclonil	0.3	1-inch flood	28	25bcde
Pyraclonil	0.3	4-inch flood	28	22bcde
Pyraclonil	0.3	3 DAF	28	39bcde
Pyraclonil	0.3	Pre-seed bare ground	42	18de
Pyraclonil	0.3	1-inch flood	42	16de
Pyraclonil	0.3	4-inch flood	42	12e
Pyraclonil	0.3	3 DAF	42	24bcde

Note. Means with the same letter within each column do not differ by Tukey's honestly significant difference $\alpha = 0.05$. Assessment dates (DATs) were analyzed as a repeated measure.

Abbreviation: DAF, days after initial flood.

[a]Injury included stunting when compared to the nontreated.

TABLE 6 Rice plant height and grain yield as affected by pyraclonil application timings on two rice cultivars in 2019, 2020 and 2023.

			2019 and 2020	2023	2019	2020	2023[a]
			Plant height (inches)		Rice grain yield (lbs ac^{-1})		
Treatment	Rate (lbs a.i. ac^{-1})	Timing	M-206	M-209	M-206		M-209
Nontreated	–	–	31b	34 ± 3	5,934	2,125	3,549 ± 1,196
Pyraclonil	0.3	Pre-seed bare ground	32a	37 ± 2	6,914	3,105	5,956 ± 761
Pyraclonil	0.3	1-inch flood	34a	39 ± 2	6,495	2,685	5,860 ± 851
Pyraclonil	0.3	4-inch flood	33a	39 ± 2	7,185	3,376	4,957 ± 1,397
Pyraclonil	0.3	3 DAF	34a	39 ± 2	6,517	2,708	5,373 ± 414
					NS	NS	

Note. 2019 and 2020 data were pooled since there was no difference in years. Means with the same letter within each column do not differ by Tukey's honestly significant difference $\alpha = 0.05$.

Abbreviations: DAF, days after initial flood; NS, not significant.

[a]The 2023 data is presented as means ± standard deviation of four replicates.

4 | RICE RESPONSE TO PYRACLONIL TIMING

Visual rice response was observed as stunting of early rice growth and dark green foliage as the season progressed. However, the rice overcame any visual injury by 42 DAT (Table 5). Rice plant height and rice grain yields appeared not affected by pyraclonil timing (Table 6). The similar grain yields to the nontreated would have been because of the reduced control in ricefield bulrush which continued interference with the rice growth after the treatments (Swain et al., 1975). While early growth rice injury appears alarming, early-season herbicide injury is not uncommon in water-seeded rice (Becerra-Alvarez et al., 2022). Water-seeded rice growers will typically use high seeding rates and accept significant failed rice seed establishment which can be caused by various environmental factors including herbicides (UCANR, 2023).

5 | WEED CONTROL RESPONSE TO PYRACLONIL IN HERBICIDE COMBINATIONS

Pyraclonil applied alone effectively controlled broadleaf weeds; however, control of sedges was increased when

TABLE 7 Average weed control at 14 and 42 days after treatment with pyraclonil alone and in herbicide combinations on water-seeded rice in 2019 and 2021.[ab]

	Ricefield bulrush		Smallflower umbrella sedge		Ducksalad		Redstem		*Echinochloa* spp.		Bearded sprangletop	
	DAT											
Treatments	14	42	14	42	14	42	14	42	14	42	14	42
	% of nontreated											
T1	31	24b	65	48b	85	86	86	94	76	54b	87	80ab
T2	61	48ab	80	68ab	100	100	100	88	76	88a	100	68ab
T3	88	97a	97	99a	100	100	100	100	86	99a	50	100a
T4	71	69ab	80	78ab	92	100	100	95	93	99a	80	99a
T5	75	88a	95	96a	100	100	100	100	96	99a	100	100a
T6	71	73a	87	81ab	100	89	100	100	95	100a	100	94ab
T7	71	87a	79	88a	100	100	100	100	88	92a	100	61b
T8	46	97a	80	97a	100	100	100	100	87	98a	100	93ab
	NS		NS		NS	NS	NS	NS	NS		NS	

Note: Means with the same letter within each column do not significantly differ with Tukey's honestly significant difference at $\alpha = 0.05$.
Abbreviations: DAT, days after treatment with pyraclonil; NS, not significant; T1, pyraclonil; T2, pyraclonil followed propanil; T3, pyraclonil followed by benzobicyclon + halosulfuron followed by propanil; T4, pyraclonil followed by clomazone followed by propanil; T5, pyraclonil followed by thiobencarb followed by propanil; T6, pyraclonil followed by propanil followed by bispyribac-sodium; T7, pyraclonil followed by penoxsulam followed by propanil; T8, pyraclonil followed by propanil followed by florpyrauxifen-benzyl. See Table 2 for herbicide rates and timings.

accompanied by other available herbicides. Benzobicyclon + halosulfuron, thiobencarb, bispyribac-sodium, penoxsulam and florpyrauxifen-benzyl combinations with or followed with propanil after pyraclonil applications increased the sedge control in this study compared to pyraclonil applied alone (Table 7).

Echinochloa control was increased when pyraclonil was in combination with other herbicides at 42 DAT (Table 7). In this study, pyraclonil alone did not provide greater than 54% control of *Echinochloa* and further demonstrate the observed inconsistencies in *Echinochloa* control that may be affected by various environmental factors like soil moisture or temperature affecting weed emergence at time of flooding. Therefore, pyraclonil can be incorporated with other herbicides to achieve season-long weed control. Bearded sprangletop was, on average, present only four to eight emerged plants per plot in the nontreated by 30 DAT and control levels with pyraclonil are inconclusive. The combinations with herbicides that have activity on bearded sprangletop like benzobicyclon, clomazone or thiobencarb can be utilized in fields known to have an abundance of bearded sprangletop (UCANR, 2023).

6 | RICE RESPONSE TO PYRACLONIL IN HERBICIDE COMBINATIONS

In 2019, visual rice injury resulted up to 79% at 14 DAT but decreased to less than 24% by 42 DAT (Table 8). However, in 2021, no injury greater than 4% and 23% was visible at 14 and 42 DAT, respectively (Table 8). The observed injury differences by year may be attributed to the variable weather conditions early in the season with lower temperatures in 2019 than in 2021 at the time of seeding (Figure S1, S2, S3). The pyraclonil followed by thiobencarb treatment demonstrated increased injury levels at 42 DAT both years (Table 8). Thiobencarb can cause significant injury if applied before the 1- to 2-rice leaf stage and has a 30-day water-holding period, which means the entering flood water must not be released from the field which limits circulation of the herbicide in

TABLE 8 Rice chlorosis and stunting at 14 and 42 days after treatment with pyraclonil applied alone and in combination with other herbicides in 2019 and 2021.[a]

	2019		2021	
	Visual injury		Visual injury	
Treatments	14 DAT	42 DAT	14 DAT	42 DAT
	% of nontreated			
T1	73ab	0b	2a	7b
T2	61ab	4b	1a	4b
T3	41ab	1b	4a	8b
T4	71ab	1b	0a	3b
T5	79a	24a	3a	23a
T6	71ab	3ab	1a	4b
T7	50ab	11ab	1a	5b
T8	25b	1b	2a	1b

Abbreviations: T1, pyraclonil; T2, pyraclonil followed pyraclonil; T3, pyraclonil followed by benzobicyclon + halosulfuron followed by propanil; T4, pyraclonil followed by clomazone followed by propanil; T5, pyraclonil followed by thiobencarb followed by propanil; T6, pyraclonil followed by propanil followed by bispyribac-sodium; T7, pyraclonil followed by penoxsulam followed by propanil; T8, pyraclonil followed by propanil followed by florpyrauxifen-benzyl. See Table 2 for herbicide rates and timings.

TABLE 9 Rice grain yield as affected by pyraclonil applied alone and in combination with other herbicides in 2019 and 2021.

Treatments	Rice grain yield	
	lbs ac^{-1}	
NTC	5,635b	3,315b
T1	6,925a	9,182a
T2	7,036a	9,737a
T3	8,623a	10,486a
T4	7,500a	10,508a
T5	8,491a	9,936a
T6	7,589a	10,013a
T7	8,353a	9,878a
T8	8,265a	10,866a

Note. Means with the same letter within each column do not differ by Tukey's honestly significant difference $\alpha = 0.05$.

Abbreviations: NTC, nontreated control; T1, pyraclonil; T2, pyraclonil followed propanil; T3, pyraclonil followed by benzobicyclon + halosulfuron followed by propanil; T4, pyraclonil followed by clomazone followed by propanil; T5, pyraclonil followed by thiobencarb followed by propanil; T6, pyraclonil followed by propanil followed by bispyribac-sodium; T7, pyraclonil followed by penoxsulam followed by propanil; T8, pyraclonil followed by propanil followed by florpyrauxifen-benzyl. See Table 2 for herbicide rates and timings.

the field (UCANR, 2023). When thiobencarb is applied after pyraclonil, the 30-day water-holding period was followed and may have resulted in concentrated herbicide levels in the plots leading to excessive absorption by the rice seedlings. However, rice grain yields were no different across treatments from 6,925 to 8,623 lbs ac^{-1} and 9,182 to 10,865 lbs ac^{-1} in 2019 and 2021, respectively (Table 9).

7 | PRACTICAL IMPLICATIONS

An application of pyraclonil within three days of rice seeding will achieve up to 90% control of smallflower umbrella sedge, broadleaves, and *Echinochloa* if applied before emergence; however, additional herbicides should be incorporated for control of ricefield bulrush and bearded sprangletop. Early-season rice injury from pyraclonil was observed; however, application timings and herbicide combinations resulted in similar grain yields in both studies. Pyraclonil will be a useful herbicide with a new mode of action for early-season weed control in water-seeded rice.

AUTHOR CONTRIBUTIONS

Aaron Becerra-Alvarez: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; validation; visualization; writing—original draft; writing—review and editing. **Sarah L. Marsh**: Conceptualization; data curation; investigation; methodology; project administration; supervision; validation; visualization; writing—review and editing. **Alex R. Ceseski**: Conceptualization; data curation; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—review and editing. **Kassim Al-Khatib**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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